Agricultural Systems 173 (2019) 209–217

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Comparing soil respiration and carbon pools of a maize-wheat rotation and switchgrass for predicting land-use change-driven SOC variations

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ARTICLE INFO

Keywords:
Maize-wheat
Switchgrass
Carbon
Soil respiration
Land-use change
DAYCENT

ABSTRACT

The deployment of dedicated energy crops and the related land-use change are topical issues, particularly in relation to carbon storage and climate change mitigation effects. In order to maximize their mitigation potential and to fully supply new biorefineries, perennial energy crops may be established, not only on former idle and grazing lands, but also on the least remunerative cropland, as indirect land use change effects are still very uncertain. Possibly becoming a future land-use change option, the carbon flows of the most common crop rotation in Europe (maize-wheat) and the perennial grass switchgrass were measured, and later included in a biogeochemical model to build possible scenarios. Yearly mean soil respiration did not statistically differ between switchgrass and the annual cereals (2.9 and 2.5 Mg CO_2 ha^{-1} $month^{-1}$, respectively), but in switchgrass the peak flux was reached during crop growth (6.1 Mg CO_2 ha^{-1} $month^{-1}$), while in the cereal system it occurred in bare soil (after harvest and soil tillage) (4.5 Mg CO_2 ha^{-1} $month^{-1}$). Harvest residues contributing to soil organic matter were highest in maize (12.4 Mg ha^{-1} y^{-1}) and decreased in switchgrass (−79%) and wheat (−87%). Root biomass was much higher in switchgrass (10.0 Mg ha^{-1} y^{-1}) than maize (−81%) or wheat (−94%). Model projections showed how continuous switchgrass cycles of 15 years following annual crops cultivation were capable to keep building up SOC inventories (0.24 or 0.32 Mg ha^{-1} y^{-1}) up to the year 2100. On the opposite, maintaining the land under maize-wheat cultivation, depending on maize stover management, would either produce a SOC loss (−3.6 Mg ha^{-1}) or could help the soil increasing SOC (+9.4 Mg ha^{-1}) towards a new equilibrium after two decades.

1. Introduction

Changes in land use and land management are estimated to have released 156 Pg of C to the atmosphere in the last 150 years (Houghton, 2003). In the past decades, the increase in world population has triggered cropland expansion to produce more food, thus causing most part of these land use-related emissions in the agricultural sector (Soussana et al., 2004; Burney et al., 2010; West et al., 2010). But, presently, there is an international commitment to reverse or, at least, mitigate global warming processes (Paris Agreement; UNFCCC, 2016), both by reducing emissions to the atmosphere and by fixing atmospheric C. Agriculture has a primary role in greenhouse gas (GHG) mitigation (Paustian et al., 2006) because it can reverse detrimental land-use changes (e.g. re-afforestation; Post and Kwon, 2000) and attenuate the pressure from land management (i.e. low inputs). For example, one way to achieve this mitigation is to cultivate perennial crops for the biofuel industry, which can increase the organic C stocks of agricultural systems (Lemus and Lal, 2005; Tilman, 2006; Anderson-Teixeira et al., 2009). Although such crops are best suited to marginal lands (Cai et al., 2011), in some cases (e.g. biomass supply districts) their cultivation may conflict with the cultivation of annual food crops in conventional agricultural areas. In this case, the substitution of conventionally tilled food crops with deep-rooted perennial bioenergy crops could potentially stock, for example, 4.5 or 6.3 Mt. C, respectively on European set-aside lands (Freibauer et al., 2004) or low-productive Mediterranean cropland (Nocentini et al., 2015); at the same time, land management-related emissions would be mitigated thanks to the lower agronomic inputs required (Fazio and Monti, 2011). Nonetheless, being mandatory for biofuel crops to be at least GHG neutral, measuring their C flows against the C flows of the annual crops that would be replaced, will allow their real mitigation potential to be estimated, for example, by integrating such data into process-based, biogeochemical models (e.g. DAYCENT; Parton et al., 1998). Until now, biofuel perennial crops cultivated on former cropland have been reported to generally increase soil organic carbon (SOC) stocks, by 6–14% (Qin et al., 2016), while fixing additional C through litter and root biomass (Tilman et al., 2006;

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https://doi.org/10.1016/j.agsy.2019.03.003
Received 16 June 2018; Received in revised form 1 February 2019; Accepted 5 March 2019
Available online 12 March 2019

Anderson-Teixeira et al., 2013; Di Virgilio et al., 2019). Furthermore, measuring the C flows caused by the land-use change from annual crops to perennial biofuel crops will help understanding and modeling the indirect land-use change (ILUC) effects, generated by the displacement of food production somewhere else, which are not yet fully understood (Plevin et al., 2010; Zilberman, 2017).

In North Italy, switchgrass (*Panicum virgatum* L.) may be used for the production of bioenergy, since this perennial crop can reach significant yields in the Mediterranean basin (Alexopoulou et al., 2015) and since, in general, it has been selected and extensively studied as a bioenergy crop since more than 20 years (Sanderson et al., 1996; McLaughlin and Kszos, 2005; Wang et al., 2015; Qin et al., 2016; Di Virgilio et al., 2019), and found able to positively impact GHG emissions (Monti et al., 2012). At the same time, the Po Valley hosts the cultivation of several food crops, among which, maize (*Zea mays* L.) and wheat (*Triticum aestivum*) particularly benefit from the favourable climatic conditions, producing substantial grain yields (ISTAT, 2010). Maize and wheat are also used in succession, especially when maize stover is reintegrated into the soil to limit the decline of soil fertility.

It is hypothesized that, within future biomass supply districts, to counterbalance the uncertain effects on C stocks of unmanaged marginal and grazed lands conversion to switchgrass (Garten and Garten Jr. and Wullschleger, 2000; Qin et al., 2016), the conversion of the least remunerative cropland may be subsidized, since this type of land-use change can be expected to store elevated amounts of carbon (Freibauer et al., 2004; Nocentini et al., 2015; Qin et al., 2016). Therefore, in the present study, soil CO_2 respiration and organic C pools, such as above-ground biomass, litter and roots C, were measured in two large fields (farm-scale) in the Po Valley (North Italy), one cultivated with maize and wheat and another one cultivated with switchgrass. The objectives of the study were to i) quantify the C flows occurring in both systems ii) compare the soil CO_2 efflux of the two cropping systems, also in relation to their different agronomic management, iii) estimate the long-term ecosystem C variation caused by the land-use change from arable crops to switchgrass in the northern Mediterranean through modeling.

To our knowledge, this is the first site studying the land-use change effects of switchgrass replacing cropland in Europe (Qin et al., 2016); these data will possibly help, with new evidence, decision-makers on the future deployment of dedicated energy crops on former European cropland, as well as in building models to assess ILUC. Furthermore, in the present study, switchgrass cultivation after arable crops was simulated for multiple cycles of 15 years (almost 90 years in total), hypothesizing what could happen to soil carbon in the case of establishing biomass supply districts around new biorefineries which would demand a continuous production of perennial crops together with agricultural residue. In alternative to land-use change to switchgrass, also the continuation of maize-wheat cultivation was simulated for several decades, hypothesizing different residue removal rates. As, at present, much importance has been given to the use of agricultural residue in the bio-economy (Sheehan et al., 2008; Valenti et al., 2018), the long-term impact of residue removal should be carefully studied.

2. Materials and methods

2.1. Experiment set-up

The trial was carried out in Cadriano (Bologna, North Italy; 44° 33′ N, 11° 24′ E; 33 m a.s.l.), on a clay loam (Udic Ustochrepts, mesic) soil (Table 1) in the experimental farm of the University of Bologna. Measurements were carried on a large switchgrass field (five hectares) and another farm-scale field (two hectares) on a maize-wheat rotation.

Switchgrass (cv. Alamo) was sown on 23 April 2012, 45 cm row spaced. Maize, wheat and sugar beet (*B. vulgaris* L. vr. *saccharifera* L.) were the former crops, cultivated in rotation for, at least, 30 years previous to switchgrass establishment. Seedbed preparation included plowing, harrowing and mechanical hoeing. Phosphate (P_2O_5, 230 kg ha^{-1}) was distributed during seedbed preparation, while N fertilizer (urea, 100 kg ha^{-1}) was applied from the second year on. Switchgrass was harvested and baled in autumn (early October). Maize (cv. Pioneer 1028, FAO 500) was sown on 1 April 2015 (70 cm inter-row) on a field that had been cropped with maize and wheat since the year 2008. It was fertilized with phosphate (P_2O_5, 70 kg ha^{-1}) at sowing, and with N (urea, 300 + 300 kg ha^{-1}) after emergence. Mechanical and chemical weed control were performed, as well as treatments against stalk borer in July. Combine harvest was carried out on 20 August without residue removal. Then the soil was plowed and harrowed in September and, on 16 October, wheat (cv. Rebelde) was sown (20 cm inter-row). N fertilizer was applied as urea in January and March (100 + 270 kg ha^{-1}), and as ammonium nitrate in April (167 kg ha^{-1}). Chemical weed control was performed and pesticides against aphids, insects and fungal diseases were also applied. Grain harvest was carried out on 24 June and, afterwards, straw was baled and removed.

Table 1
General soil characteristics of the two experimental fields (0–0.45 m).

	Switchgrass field	Maize-wheat field
Gravel (> 2 mm) (%)	ns	ns
Sand (0.05 mm < 2 mm) (Particle size an.) (%)	29	21
Silt (0.002 mm < 0.05 mm) (Particle size an.) (%)	39	51
Clay (< 0.002 mm) (Particle size an.) (%)	32	28
pH	7.2	7.6
Total N (Dumas) (g kg^{-1})	1.2	1.4
Total limestone (Dietrich-Fruehling) (%)	1.0	7.5
Available P (Olsen) (mg P_2O_5 kg^{-1})	57	30
Exchangeable K (mg K2O kg^{-1})	161	161

ns = not significant.

In both fields, seven sampling areas of 6 m^2 (3 m × 2 m) were established, randomly distributed on the large surfaces. Inside these sampling areas, various measurements were performed in order to study the size of the C pools and the C flows of the two systems.

Minimum, maximum, average temperature and daily precipitations were recorded by a meteorological station placed inside the experimental farm. Long-term (25 years) yearly average minimum and maximum temperatures and cumulated precipitations for the site corresponded to 12.4 ± 2.6 °C, 22.7 ± 1.6 °C and 595 ± 218 mm, respectively.

2.2. Carbon pools

The above-ground biomass was manually harvested in all sampling areas in switchgrass (October 2012, 2013, 2014, 2015 and 2016), maize (August 2015) and wheat (June 2016). For the two cereals, grains were separated from the rest of the plant using a small combine harvester (Wintersteiger AG). Residue from wheat (harvest losses) was measured after grain mechanical harvest and straw baling, whereas in maize, being only the grain harvested, all the remaining biomass was considered residue; residue from maize and wheat was always left on field and embedded into the soil with tillage. Also in switchgrass, after each mechanical harvest, losses were measured on 6 m^2 surfaces. Total litter biomass in switchgrass, composed by recent losses, harvest losses from previous years and, in smaller proportion, by leaves fallen during the growing season, was measured on 0.25 m^2 areas by collecting all the material (dead stems and leaves at different stages of decomposition) present between the surface exposed to the atmosphere and the soil surface. Biomass, grains and litter moisture content was determined on oven dried (105 °C) sub-samples after 72 h.

In each sampling area, at each sampling date (crops' harvest), three soil cores (70 mm ϕ) were collected by a mechanical auger coupled

with a tractor down to 0.45 m soil depth, split in three increments: upper layer (0–0.15 m), intermediate layer (0.15–0.30 m) and deep layer (0.30–0.45 m). In each sampling area, the three soil cores were collected within the row, next to the row and in the inter-row, respectively, to take into account spatial differences in root biomass. In total, 441 soil cores were collected throughout the experiment (switchgrass, 7 samplings × 3 replicates × 3 depths × 5 years; maize-wheat, 7 samplings × 3 replicates × 3 depths × 2 years). Samples were air-dried: then litter residues were manually removed and root biomass was manually separated from the soil, washed, sieved and oven dried (105 °C) for 72 h.

The C content of above-ground, root, litter and residue biomass was always considered its 40%.

2.3. Soil respiration

Inside each sampling area, two plastic rings (10 cm diameter) were hammered into the soil, one in the row and one in the inter-row; the rings, 10 cm long, were hammered 5 cm into the soil. Soil respiration measurements were performed weekly in 28 rings during the growing season (April–October), and twice a month in the dormant period (November–March). Measurements started in May 2015 and ended in October 2016. Soil respiration was measured by an infrared gas analyzer (EGM-4 instrument, PPSystems, USA) coupled with a soil respiration chamber (volume = 1.3 l). The measurements were always performed in parallel in switchgrass and in the rotation field, between 7.00 and 10.00 am, as our previous tests (data not shown) showed that from 7.00 to 10.00 (and from 20.00 to 22.00) the efflux from the soil corresponded to the daily average.

2.4. Statistical analysis

All measured data were subject to repeated measures analysis of variance (ANOVA). Fisher's LSD ($P \leq 0.05$) test was used to separate means when ANOVA revealed significant differences ($P \leq 0.05$).

2.5. Model parameterization and evaluation set-up

The DAYCENT model (Parton et al., 1998; Del Grosso et al., 2011) was designed to simulate, using a daily time step, cycling of C, N and water in natural and agricultural systems based on biophysical factors, current and historical land use, vegetation cover and management practices.

In this study, the modeling approach was to adjust DAYCENT's site-specific and crop-specific parameters, leaving unchanged the standard set of general parameters. Hence, after having set soil (Table 1) and site characteristics, crop-specific parameters were adjusted by hand, in a plausible way, in order to simulate the C flows measured in the switchgrass and maize-wheat fields.

Parameterization of switchgrass for the same field is already described in Nocentini et al. (2015). Nevertheless, the parameterization was further refined by using two more years of above- and below-ground biomass yields and one additional year of CO_2 fluxes (*GPP* = gross primary production; *ER* = ecosystem respiration; *NEE* = net ecosystem exchange) measured by an eddy covariance system which was placed at the center of the field since establishment (Di Virgilio et al., 2019). Also soil respiration fluxes (*Sresp*) measured within this study further improved model calibration for switchgrass. As in Nocentini et al. (2015), the life cycle of a switchgrass stand was divided in phases in order to simulate a decline in yields after some years: i) establishment (year 1), ii) maximum yielding phase (years 2–6), iii) mature phase (years 7–11) and iv) old phase (years 12–15). Parameterization for maize and wheat has already been achieved in previous studies (Del Grosso et al., 2005; Stehfest et al., 2007; Del Grosso et al., 2016), therefore here only parameters that control growth rate (*Prdx*), plant carbon allocation (*Frtc*, *Himax*) and the rates of maintenance and growth respiration (*Ckmrspmx*, *Cmrspnpp*, *Cgresp*) were further adjusted in order to simulate the organic C pools of the specific cultivars used in the Po Valley.

Since the principal objective of the future scenarios (see next section) was the long-term projection of SOC stocks under different land-use managements, model evaluation was then performed by using SOC data from long-term trials carried out in the same farm or nearby areas. Specifically, the 10-year SOC change measured beneath switchgrass by Nocentini and Monti (2017) in Bologna (44° 34′ N, 11° 47′ E), the 14-year SOC change (unpublished) measured in Ozzano dell'Emilia (44° 25′ N, 11° 28′ E) in a switchgrass field established in 2002 (Di Virgilio et al., 2007), and the 35-year SOC change measured in a maize-wheat rotation under different management practices in Cadriano (Bologna) experimental farm (Triberti et al., 2008) were used. Before each model run, SOC was initialized by running an equilibrium phase of several thousand years where in the last centuries first plow-out and crops rotation followed the original natural vegetation. Since DAYCENT simulates SOC dynamics and stocks only for the upper 20–30 cm of the soil, all simulated SOC variations were compared with observed changes in SOC occurring in the upper soil.

2.6. Simulation scenarios set-up

Different future scenarios were simulated comparing either land-use change from annual arable crops (i.e. sugar beet, maize, wheat) to switchgrass or the continuation of the maize-wheat rotation. In each scenario, lignocellulosic biomass and grain productivities and SOC stocks variation were simulated up to the year 2100. Two scenarios for land-use change to switchgrass were built: one where switchgrass was unfertilized and one where 67 kg N ha^{-1} y^{-1} were applied, starting from the second year of cultivation, as this rate was identified as best management practice in a previous study (Wang et al., 2015). Switchgrass harvest was simulated at the beginning of October every year, with 85% biomass removal rate on total aboveground production (15% residue). The life span of a switchgrass stand was considered 15 years; thereafter, the soil was tilled and switchgrass was sown again after seedbed preparation.

Three scenarios were built in which the maize-wheat rotation continued, each considering a different management of maize stover: i) no residue removal, ii) 50% residue removal, iii) 90% residue removal. Fertilization rates were maintained equal to those normally applied in the region both for maize and wheat (i.e. same as applied in this experiment), while wheat straw was removed in every scenario since it is a standard practice in the region. On the opposite, maize stover may be left on field or harvested as biomass for different uses (e.g. energy). For this reason, maize stover removal was varied in the three scenarios.

In all five scenarios, in the decades before establishing switchgrass or before continuous maize-wheat, the land use was constituted by standard rotations including maize, wheat, sugar beet and alfalfa (*Medicago sativa* L.).

3. Results and discussion

3.1. Above- and below-ground biomass C

Harvested biomass was highest in wheat and corresponded to 13.7 Mg ha^{-1}, taking into account both grain and straw (7.2 and 6.4 Mg ha^{-1}, respectively). In maize, only the grain biomass was harvested (7.5 Mg ha^{-1}), while stover biomass (12.4 Mg ha^{-1}) was completely left on field as residue.

Switchgrass showed comparable yields from the second to the fifth year (16.6, 15.8, 15.7 and 14.4 Mg ha^{-1}, respectively), although the composition between harvested biomass and residues differed (22%, 34%, 23% and 13% of residues from the second to the fifth year, respectively). Harvest losses were lower or higher, depending on the condition of the biomass (e.g. lodging). Therefore, C inputs to the

Table 2
Grain productivity, lignocellulosic biomass productivity, net SOC change and net ecosystem C change for each of the five simulated future scenarios.

Scenario	Grain dry yield	Harvested lignocellulosic dry biomass	SOC change	Ecosystem C change
	$Mg\ ha^{-1}\ y^{-1}$	$Mg\ ha^{-1}\ y^{-1}$	$Mg\ ha^{-1}$	$Mg\ ha^{-1}$
Ma-Wh (no residue removal)	7.0	3.0	9.4	9.5
Ma-Wh (50% residue removal)	7.0	6.0	2.3	2.4
Ma-Wh (90% residue removal)	7.0	8.4	−3.6	−3.5
Sg (unfertilized)	–	6.2	20.9	23.6
Sg ($67\ kg\ N\ ha^{-1}\ y^{-1}$)	–	8.9	28.0	30.7

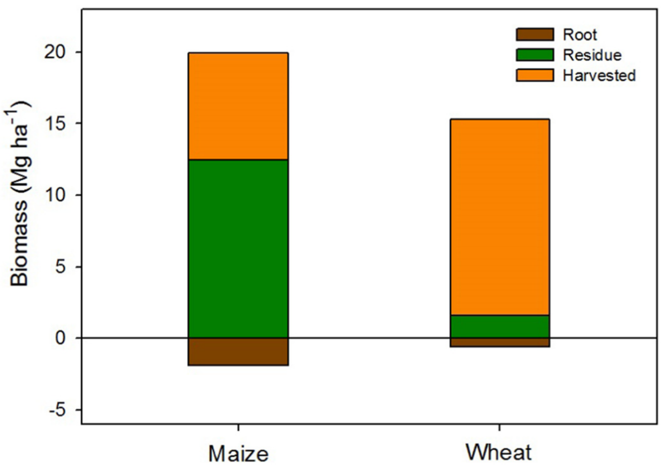

Fig. 1. Below- (root) and above-ground (harvested + residue) biomass production measured in maize and wheat at Cadriano experimental farm in North Italy in the years 2015 and 2016. In maize only grain was harvested, resulting in high residue, while in wheat both grain and straw were harvested, resulting in low residue.

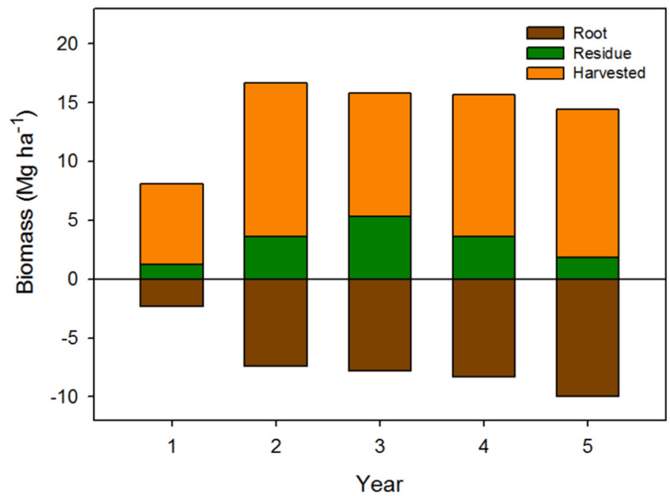

Fig. 2. Below- (root) and above-ground (harvested + residue) biomass production measured in switchgrass at Cadriano experimental farm in North Italy between the years 2012 and 2016.

system through residues were much higher in maize than in switchgrass (−79%) or wheat (−87%). On the other hand, differently from maize and wheat, switchgrass residues were not embedded into the soil with tillage, so they increased the litter layer covering the soil which, at the end of the fifth year, reached 12.3 $Mg\ ha^{-1}$ of dry biomass, an amount that equaled the litter biomass measured in a riparian buffer in central Iowa under the same vegetation (Tufekcioglu et al., 2003). Although lower, even Garten et al. (2010) measured high litter biomass (~11 $Mg\ ha^{-1}$) after four years of cultivation of an annually harvested switchgrass stand. Also in the present study switchgrass was harvested every year, but dry biomass inputs from harvest losses to the litter layer totaled 15.6 $Mg\ ha^{-1}$ in five years (Fig. 2), and more contribution derived from leaves fall during the growing season, explaining the high value found. Looking at root biomass, switchgrass showed a root dry biomass that was already 7.4 $Mg\ ha^{-1}$ at the end of the second growing season and that reached 10.0 $Mg\ ha^{-1}$ at the end of the fifth season, greatly surpassing both maize and wheat root biomass (1.9 and 0.6 $Mg\ ha^{-1}$, respectively); Tufekcioglu et al. (2003) also reported switchgrass to have about five times more root biomass than maize (~10 and ~2 $Mg\ ha^{-1}$, respectively), while Anderson-Teixeira et al. (2013) measured seven times more root biomass in switchgrass than maize (9.0 and 1.2 $Mg\ ha^{-1}$, respectively). Further, while in maize and wheat most of the root biomass was found in the upper layer (77 and 86%, respectively), in switchgrass only 48% was in the upper soil, with 19% of root biomass (1.8 $Mg\ ha^{-1}$) measured in the deep layer. Previously, Monti and Zatta (2009) had found even more root biomass in the deep layer (43%) than in the upper (31%) and intermediate (26%) layers under switchgrass. Substantially higher root biomass in the deeper soil layers in switchgrass compared to annual crops, will probably enhance C deposition and increase SOC inventories in the deep soil in the event of a land-use change to switchgrass after long-term cultivation of annual cereals. Furthermore, the outstanding amounts of litter and root biomass in switchgrass represent semi-permanent C stocks on the soil surface and in the soil that will not be disturbed for as long as the stand is maintained (Di Virgilio et al., 2019), ultimately benefitting the ecosystem C balance (Tilman et al., 2006; Anderson-Teixeira et al., 2013). Organic C pools were instead much lower in the maize-wheat system and were anyway often disturbed, triggering re-emission of CO_2 to the atmosphere (Fig. 3; Hendrix et al., 1988), and resulting in a considerable gap in ecosystem C between these two land uses.

3.2. CO_2 respired from the soil

Soil respiration was monitored in maize-wheat and switchgrass during 18 months (May 2015 to October 2016). Although the annual soil respiration rate did not statistically differ between crops (2.89 and 2.49 $Mg\ CO_2\ ha^{-1}\ month^{-1}$ in switchgrass and maize-wheat, respectively), soil respiration in switchgrass showed a more regular trend than in the annual cereals (Fig. 3). This was likely due to the reduced soil tillage of the perennial crop (Hendrix et al., 1988). The no-till management allowed the formation of a thick litter layer under switchgrass, which likely mitigated the effects of precipitation and temperature on soil respiration.

During the growing season, mean soil respiration was higher in switchgrass (3.74 $Mg\ CO_2\ ha^{-1}\ month^{-1}$) than in maize or wheat (2.97 and 3.08 $Mg\ CO_2\ ha^{-1}\ month^{-1}$, respectively). As discussed later in this section, this was likely the result of a higher root-associated respiration during the growing season in switchgrass, directly related to its bigger root apparatus (Fig. 2). Anderson-Teixeira et al. (2013), after measuring, as in the present study, higher root biomass and higher soil respiration in established switchgrass than in maize, using a root exclusion technique, showed that root-associated respiration was in fact

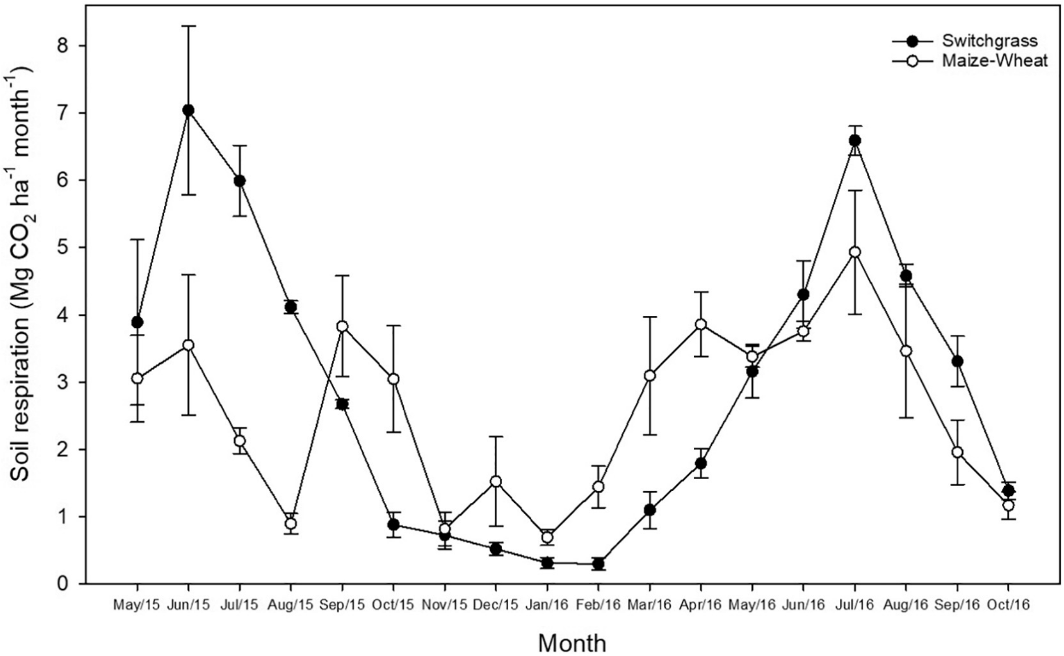

Fig. 3. Soil respiration measured at Cadriano experimental farm (North Italy) during the years 2015 and 2016. A five-ha field cultivated with switchgrass (established in the year 2012) and a two-ha field on a maize-wheat rotation are compared. *Error bars* 1 SE.

Fig. 4. Soil respiration in switchgrass and maize-wheat averaged for the periods where the soil was covered by an actively growing crop or was with bare soil (maize-wheat) or with the crop dormant (switchgrass and wheat in winter). The difference between a perennial no-till system and a conventional tilled system with annual crops is shown. *Error bars* 1 SE; *Letters* Significance groupings at $p \leq 0.05$.

significantly higher in the perennial grass system. Tufekcioglu et al. (1998) also reported similar soil respiration rates under switchgrass or maize (4.07 and 2.64 Mg CO_2 ha^{-1} $month^{-1}$, respectively) during a growing season in Central Iowa, while Rochette et al. (1991) measured much higher mean rates in maize or wheat (~10.89 and ~7.37 Mg CO_2 ha^{-1} $month^{-1}$, respectively) between May and August in two large fields in Canada than reported here. Conversely, during the dormant period (November to March), mean soil respiration was double in the maize-wheat field than in the switchgrass field (0.51 Mg CO_2 ha^{-1} $month^{-1}$), but still lower compared to the growing periods. Soil respiration in the maize-wheat field reached peak mean values in the five weeks after the first year plowing (4.07 Mg CO_2 ha^{-1} $month^{-1}$), and in the seven weeks after wheat harvest (4.84 Mg CO_2 ha^{-1} $month^{-1}$); these increases in the soil CO_2 efflux appeared closely linked to the soil disturbance caused by the intense management. Soil respiration was significantly ($P \leq 0.01$) higher in the vegetative period (April–October) than in the dormant period (November–March) in switchgrass (Fig. 4). Conversely, soil respiration was not statistically different in the maize-wheat field between periods of crop growth and periods with bare soil (Fig. 4). As discussed above, this was the result of the different managements of the two fields: in maize-wheat, after soil tillage, with bare soil, soil respiration increased, while in switchgrass soil respiration suddenly decreased after harvest, since the soil was not tilled and the litter layer acted as a physical barrier (Ryan and Law, 2005), lowering the CO_2 efflux from the soil. Hence, in maize-wheat the heterotrophic component of yearly soil respiration might have been higher than in the switchgrass system. A land-use change from maize-wheat to switchgrass could therefore mean lower SOC losses in the periods outside of the growing season.

It was not in the scope of this experiment to partition soil respiration (Subke et al., 2006), therefore it is not possible to estimate the amount of respired C that derived from organic matter decomposition (heterotrophic respiration) and how much of the respired C derived from root growth and maintenance (autotrophic respiration), and thus the net system C loss. Some indications could be however derived. For example, maize and wheat had three or eleven times higher soil respiration, respectively, than switchgrass, when based on the amount of root biomass. Likely, in switchgrass, root-associated respiration was high, although it could derive both from autotrophic root respiration or from enhanced microbial heterotrophic respiration within the rhizosphere (i.e. priming effect; Kuzyakov, 2010); in any case, switchgrass' high root biomass certainly increased soil respiration, in part by boosting its growth and maintenance (autotrophic) components (Tufekcioglu et al., 2001; Ryan and Law, 2005; Subke et al., 2006). The relation between roots and soil respiration was investigated by comparing the efflux on the row and on the inter-row in switchgrass and maize. In switchgrass, respiration on the row was 13% higher than on the inter-row, while this difference was much more pronounced in maize and was also significant (+118%) ($P \leq 0.01$); a significant difference between respiration on the row and on the inter-row in maize was already reported by Rochette et al. (1991). In switchgrass, the narrower inter-row and the larger extension of the root architecture likely diminished this difference between rows and inter-rows. Finally, as depicted in Fig. 4, also seasonal patterns can help in a partial

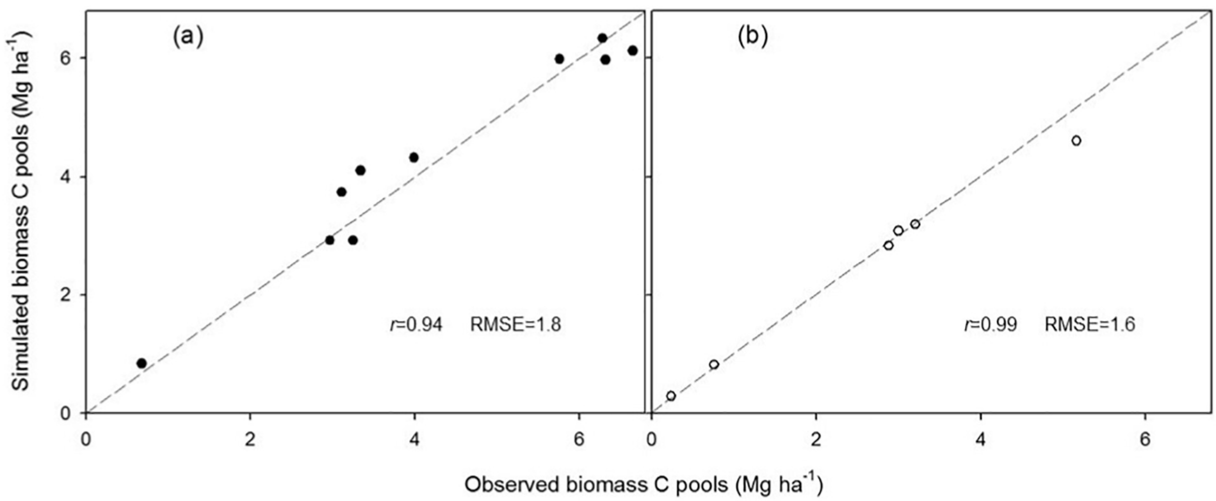

Fig. 5. Observed versus simulated biomass (root, stems + leaves, grain) C pools in switchgrass (a) and in maize-wheat (b) obtained during DAYCENT calibration.

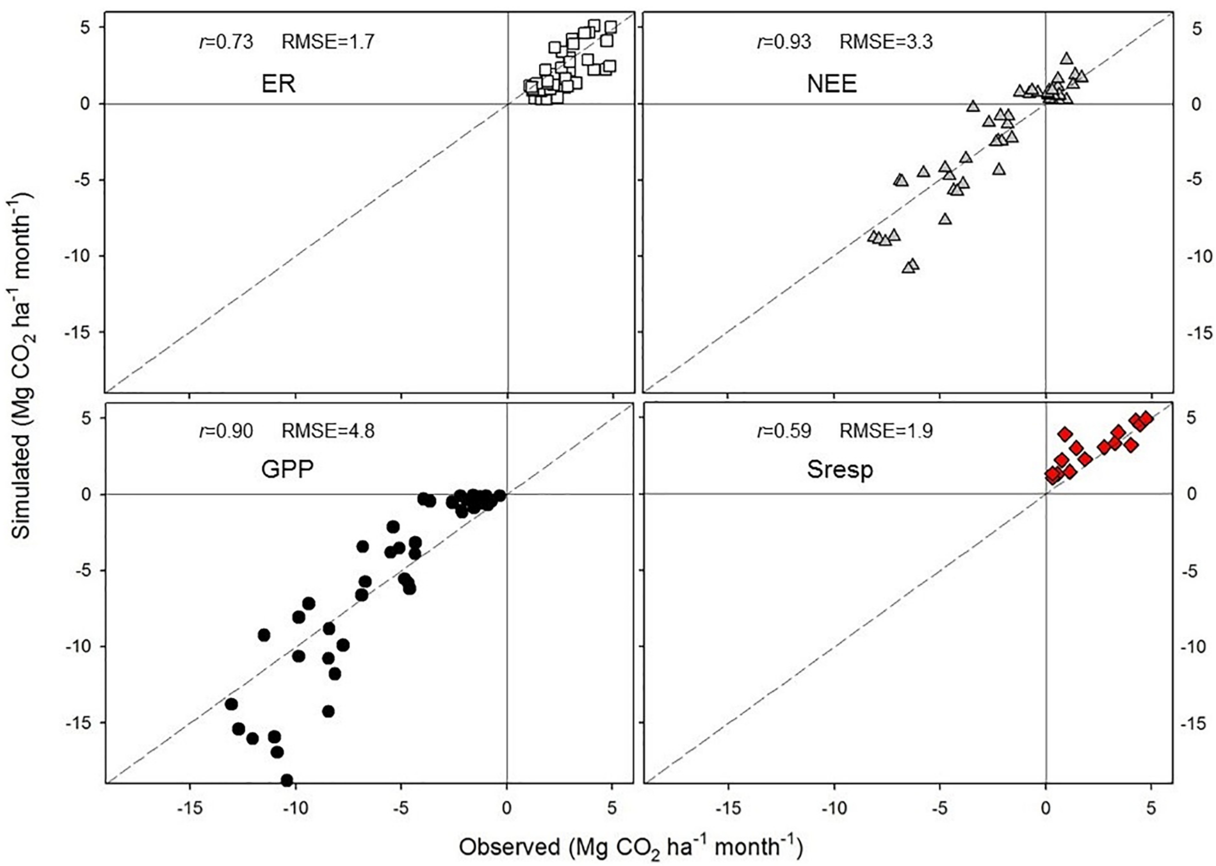

Fig. 6. Observed versus simulated ecosystem CO_2 fluxes in switchgrass obtained during DAYCENT calibration. Soil respiration was measured by a portable chamber connected to an infrared gas analyzer. All other fluxes were measured by an eddy-covariance tower placed in the field since switchgrass establishment (Di Virgilio et al., 2019). *ER* = Ecosystem Respiration; *GPP* = Gross Primary Production; *NEE* = Net Ecosystem Exchange; *Sresp* = Soil Respiration.

understanding of the relative contributions of roots and decomposition to soil respiration (Ryan and Law, 2005). Thus, if a significant portion of soil respiration in switchgrass is autotrophic while a significant portion of soil respiration in maize-wheat is heterotrophic, the land-use change from annual cereals to switchgrass would result in a substantial ecosystem C accretion, as shown elsewhere (Anderson-Teixeira et al., 2013).

3.3. Modeling C pools, flows and long-term SOC

Below- and above-ground biomass C pools were simulated using the DAYCENT model for both switchgrass and wheat-maize rotation (Fig. 5).

The results of simulated switchgrass ecosystem CO_2 fluxes are shown in Fig. 6. Simulated *NEE* correlated better with the observations than *GPP*, and much better than *ER* and *Sresp*. This is due to the fact that *NEE* corresponds to the net CO_2 fixation in the biomass and in the soil, while all other fluxes include an autotrophic respiration component,

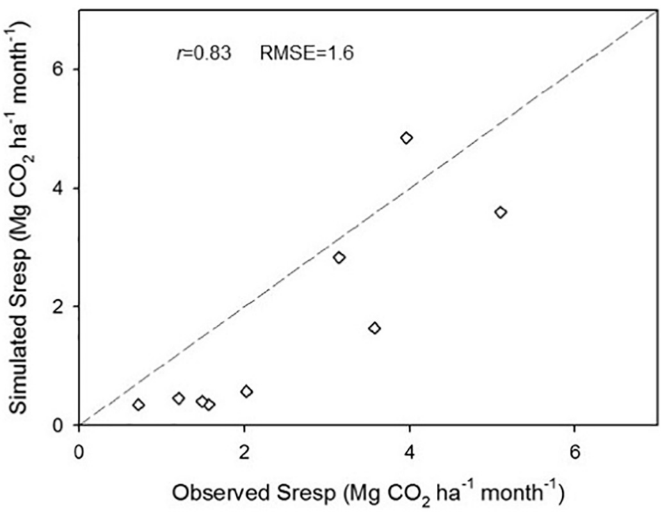

Fig. 7. Observed versus simulated soil CO_2 respiration in maize-wheat in periods with bare soil, obtained during DAYCENT calibration.

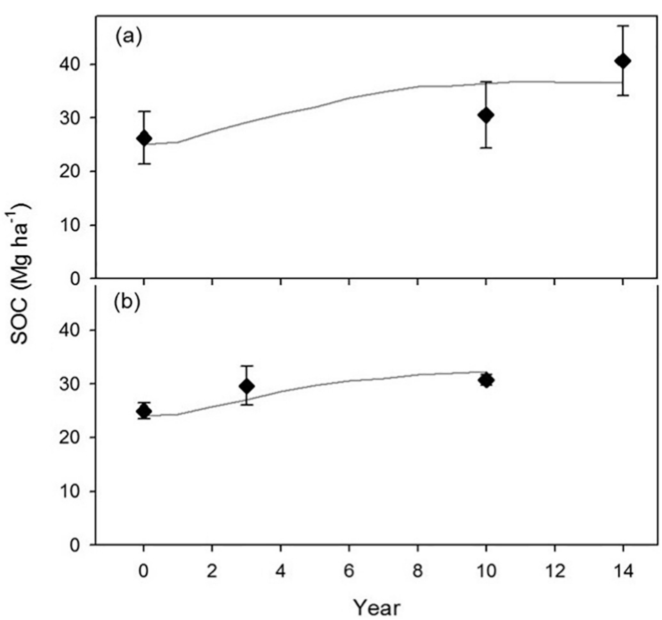

Fig. 8. Observed (diamond) versus simulated (line) SOC stocks dynamic in switchgrass for Ozzano (a) and Campotto (b) sites in North Italy. *Error bars* 1 SE.

which is harder to quantify and subsequently to model, but which is, at the same time, not as significant since it represents CO_2 quickly captured and re-emitted. Hence, in terms of sustainability, *NEE* is the most accurate and comprehensive parameter.

Similarly, in maize-wheat, although underestimated, *Sresp* dynamic was fairly reproduced by the model for periods with the soil not covered by growing vegetation (i.e. periods where autotrophic respiration is null; Fig. 7), confirming that DAYCENT's results were reliable when simulating net ecosystem C fluctuations.

Finally, long-term SOC variations were simulated for switchgrass (Fig. 8) and maize-wheat (Fig. 9) and compared with observations for model evaluation.

For both system, the model was able to predict the long-term change in SOC, although the simulated short- or mid-term SOC changes in switchgrass were not accurate, as DAYCENT predicted a faster (Fig. 8a) or a delayed (Fig. 8b) SOC stock build-up.

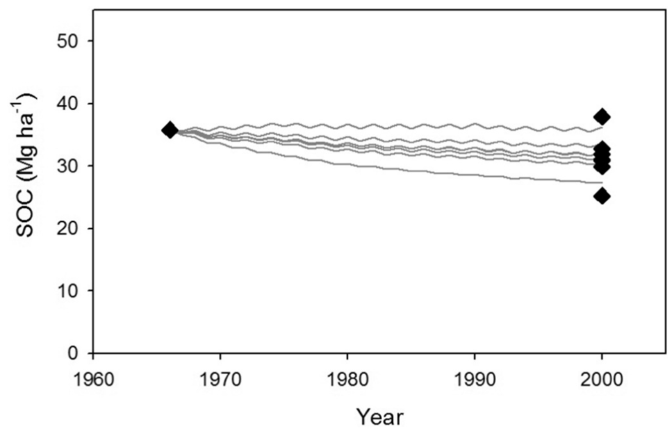

Fig. 9. Observed (diamond) versus simulated (line) SOC stocks dynamic in maize-wheat rotations with different N fertilization managements (mineral and organic), measured in a long-term experiment at Cadriano farm in North Italy.

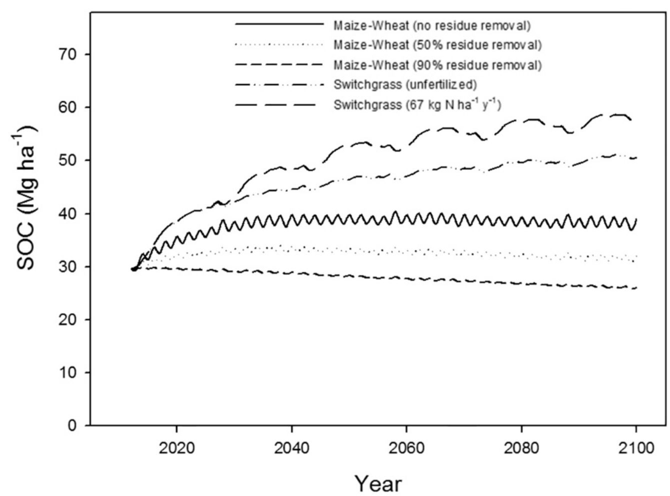

Fig. 10. Modelled SOC stocks dynamics in switchgrass and maize-wheat until the year 2100, including scenarios with different fertilization and residue managements, after land-use change from standard crop rotations typical of the Po Valley (North Italy).

3.4. Predicting land-use change-driven SOC trends

In each of the three scenarios where maize-wheat was cultivated, grain yields remained equivalent (Table 2), irrespective of the different amounts of residue re-embedded into the soil. On the opposite, the amount of harvested lignocellulosic biomass of the rotation was much higher (+180%) when maize stover was removed from the field (90% removal) than when completely re-embedded. With maize stover removal, harvested lignocellulosic biomass in maize-wheat was almost as high as in fertilized switchgrass (8.4 and 8.9 Mg ha^{-1} y^{-1}, respectively). However, the complete removal of maize stover also caused a small but progressive decline in SOC, while in both scenarios hypothesizing land-use change to switchgrass SOC increased at a good rate (0.24 and 0.32 Mg ha^{-1} y^{-1}), without even reaching a plateau by the year 2100 (Fig. 10). These long-term SOC accumulation rates are very close to what estimated by Post and Kwon (2000; 0.33 Mg ha^{-1} y^{-1}) for grassland replacing cropland (in their study, long-term data up to 81 years in length were used). Further, Soussana et al. (2004) estimated, for temperate ecosystems, that the land-use change from cropland to grassland would produce, on average, an overall (steady-state to steady-state) SOC increase of 25 ± 7 Mg ha^{-1}. Accordingly, in the present simulation, the SOC increase produced by land-use change from maize-wheat to switchgrass after 88 years corresponded to

20.9–28.0 Mg ha^{-1}. In both scenarios where maize stover was partially (50%) or completely left in the field SOC increased in the first 20–30 years after change in management (0.11 and 0.47 Mg ha^{-1} y^{-1}, respectively) to then reach steady-state (Fig. 10). Although the amount of residue left on field was higher in maize (scenario with 100% maize stover re-integration) than in switchgrass, this C input would only occur every other year. Moreover, the C input from roots turnover was much greater in switchgrass than in maize or wheat (Fig. 1 and Fig. 2). Hence, also considering that enhanced re-emission of organic C due to tillage operations would occur every 15 years in switchgrass but every year in maize-wheat, it is probably explained why switchgrass was able to accumulate more SOC (+120 to +200%; Table 2), for a much longer period (up to year 2100; Fig. 10).

It is interesting to observe how, in each switchgrass cycle, SOC increased in the first years after establishment when plant's above- and below-ground growth is enhanced, to later reach equilibrium or slightly decline when the stand became older. Nonetheless, at each new cycle, switchgrass was able to reach a new equilibrium with higher SOC inventories up to the year 2100. However, as expected, SOC sequestration rate in switchgrass declined with time. SOC sequestration rate evolved from over 1 to 0.7–0.8, and then to 0.5–0.6 Mg ha^{-1} y^{-1} after 10, 20 or 30 years, respectively. These results agree with the findings from the meta-analysis performed by Qin et al. (2016) in which, taking into account data from studies up to 24 years in length, they found that SOC sequestration in switchgrass following annual crops was, on average, 0.60 Mg ha^{-1} y^{-1} in the upper 30 cm of the soil. While, when only considering the first years of cultivation, SOC accumulation was usually above 1 Mg ha^{-1} y^{-1} (Monti et al., 2012; Qin et al., 2016). Although 58 to 65% of the C increase occurred in the first 20 years, in the following 68 years SOC increased by other 7.3 and 11.8 Mg ha^{-1}, in unfertilized and fertilized switchgrass, respectively. Additional C was sequestered by switchgrass in the root and litter biomass (2.7 Mg ha^{-1} at the end of the cycle, with a peak of 5.5 Mg ha^{-1} at the sixth year). Similarly, Anderson-Teixeira et al. (2013) and Di Virgilio et al. (2019), after four years of switchgrass cultivation, measured, 4.5 and 8.4 Mg C ha^{-1} stored in roots and litter. Although it is true that root and litter C pools are easily decomposable and their C is only transitorily sequestered, if continuous switchgrass cycles are assumed, root and litter C pools will build up at every new cycle, constituting a semi-permanent C stock.

It is out of the scope of the present research to assess the life-cycle GHG impact of the studied land-use change, but it must be stressed that, more likely, additional GHG savings would be obtained thanks to the lower agronomic inputs use (Fazio and Monti, 2011) and lower biogenic N_2O emission (Don et al., 2012) in switchgrass compared to the replaced annual crops system. On the opposite, although very uncertain (Plevin et al., 2010; Zilberman, 2017), ILUC emissions may reduce or even offset the discussed GHG benefits.

4. Conclusions

Land-use change from annual food crops to perennial biomass crops should not endanger food security, but only occur in the least remunerative areas. Nonetheless, additional studies are needed to better understand the carbon implications and climate mitigation effects as land shifts from intensively grown conventional crops (e.g. wheat and maize) to sustainable perennial crops such as switchgrass. The present study showed that, in the northern Mediterranean, the land-use change from commonly grown annual cereals (wheat and maize) to switchgrass could lead to significant benefits in terms of ecosystem C balance. Nonetheless, ILUC may or may not significantly change this outcome, therefore, more accurate methods for its estimation, that take into account also belowground biomass and SOC changes, are needed. Quite surprisingly, in future potential biomass supply districts where switchgrass could be cultivated in consecutive multiple cycles, soil C inventories might be boosted in the first years of each new cycle towards a new, higher equilibrium for many decades. If this is true, C fixation by switchgrass and other perennial bioenergy grasses following annual arable crops might be higher than presently assumed by studies that considered limited periods of time. This finding should be confirmed by designing experiments with consecutive agricultural cycles of perennial crops testing their long-term, multi-cycle productivity and SOC variations. Also, different management options for the agricultural residue deriving from maize-wheat rotations will differently affect soil C inventories of cropland in the long-term. Hence, the use of this agricultural residue for energy purposes as opposed to the land-use change to dedicated energy crops, often regarded as a more sustainable solution, may not always generate higher benefits. Particularly, in districts where there is cropland with lower productivity and revenue, or in regions with surplus production of commodities, a partial land-use change to switchgrass could likely result in the maximization of GHG savings, since the possible ILUC impact would be not significant and higher biomass for bioenergy would be collected, maintaining, at the same time, higher ecosystem C stocks.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2019.03.003.

Acknowledgements

The present study was supported by the European Project: "Optimization of Perennial Grasses for Biomass Production" (OPTIMA - EU-FP7, 289642).

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